REVOLUTIONARY ARCHITECTURES FOR FUTURE EARTH OBSERVATIONS: Observations and the Intelligent Sensorweb

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ABSTRACT

Advances in sensors, flight data systems, and communications technologies carry the promise of a radical shift in the approach to making observations of the Earth, its systems, and its interconnected systems (biosphere, atmosphere, hydrosphere, cryosphere, lithosphere and magnetosphere). Instead of performing point investigations and launching assets pre-configured for measuring a limited set of parameters, it will become possible to develop a space and ground based observational infrastructure that can quickly be configured to form new virtual instruments and platforms as needed by science, government, and commerce. Analogous to present day information networks, the system will have indefinite life, even as its pieces are replaced and its capabilities are enhanced. Advanced remote and *in-situ* sensors will enable new types of Earth science and heritage measurements of much greater sensitivity. Interoperability including auto-meshing and self-adaptation of the modeling, forecasting, and observational systems will allow optimized end to end performance.

1 INTRODUCTION

Limitations in technological capabilities have forced earth scientists into treating the Earth System as a set of semi-independent entities with highly simplified treatment of the energy and matter exchanges at the interfaces. The actual Earth System is a highly coupled set of systems with exchanges occurring in highly distributed and mostly poorly observed interfaces. The ability to examine any and all parameters of the Earth System as a fully integrated entity and at any desired spatial and temporal scale should greatly improve our ability to understand and predict the behavior of the Earth on any of those scales. In addition, it is likely to reveal insights and subtleties of behavior which are invisible to us today.

2 MULTIPLE PERSPECTIVES AND NEW VANTAGE POINTS

If one considers complex systems, for which we have a good understanding and ability to model and predict, the usual path to understanding began with the ability to visualize behaviors, which were beyond un-augmented sensory capabilities. For example, our knowledge of aerodynamics did not begin with computational fluid dynamics. Rather, it began with simulations in wind tunnels and with visualizations of the movement of the air via smoke and yarn streamers. In Earth science, scientists have long been constrained to a very limited set of *in-situ* sensors coupled with satellite measurements by the expense and capability of space assets. In particular, launch costs and capabilities and the available performance of the instruments have lead to an over reliance on low Earth orbit (LEO) measurements with a very limited utilization of geostationary Earth orbit (GEO). In addition, communication and computational inadequacies lead to an intentional set of limiting compromises in spatial and spectral resolution and in observations made.

Fortuitously, the technology is emerging that will allow the utilization of many vantage points to provide the optimum perspective or perspectives to view expected phenomena and allow serendipitous insight into the unexpected. Large aperture lightweight and/or deployable optics allow cost effective high-resolution systems in other than LEO orbits. Advances in avionics, miniaturization, and emerging production line environments are leading to dramatically lower costs while improving the available performance envelope. Highly capable flight data storage and processing systems coupled with high bandwidth communications have removed or soon will remove many of the roadblocks to an array of system level capabilities. As a result, the synoptic perspectives of a full disc of the Earth from the Earth-Sun libration points (L1 and L2), GEO, and Molniya orbits are becoming available to us at reasonable cost. In addition, the close range available from LEO orbits greatly facilitate the use of emerging active sensors, high-resolution spatial sensors, and provide good vantage points for limb observations. Low cost, highly robust electronic production capabilities offer the opportunity to deploy large arrays of many different kinds of remote and *in-situ* sensors. The ability to make observations from any and all of these vantage points and to flexibly retrieve and couple the data cannot help but reveal new insights.

3 RATIONALE FOR MANY SENSORS AND AN END-TO-END INFORMATION SYSTEM

Earth Science activities are critical to the future of humankind. In addition to extending human knowledge and satisfying human curiosity, the application of that knowledge to sustainably developing and supporting a high quality of life for human life is paramount. One can gain insight into the scientific and technical improvements that will be necessary in order to dramatically increase the impact on the well being of humankind and the Earth as its home by examining a few specific cases. For example, let us ask three questions relating to a subject we will loosely call weather over about six orders of magnitude in temporal scale. At the long end of that scale is short-term climate or seasonal to inter-annual variations. At the short end are severe weather events such as thunderstorms and hurricanes.

We ask:

1) Can we predict seasonal variations in precipitation and temperature from the norms with sufficient accuracy in both magnitude and timing to enable strategic agriculture and management of other similar activities? In other words, can we make these predictions with sufficient quality over a full growing season to allow farmers to select crop types and management strategies to increase production, mitigate the effects of adverse conditions, and take maximal advantage of beneficial conditions?
2) Can we improve mid-term weather predictions (rainfall, temperature, and wind) out to periods of many days or a few weeks to facilitate the management of weather sensitive activities such as precision farming, outdoor recreation, transportation, and fishing? For example, can we provide accurate weather predictions far enough in advance to allow farmers to make high return decisions on the timing of planting, harvesting, fertilization, and pest management?
3) Can we improve the detection, prediction, and dissemination of information about short-term weather events to dramatically mitigate their adverse effects? For example, can we substantially decrease the numbers of lives lost in severe storms and floods by providing precision local warning and real-time forecasts into the hands of every affected person? Can we provide high quality, localized information to emergency response organizations and substantially improve their ability to mitigate the adverse effects of storms?

If we can answer these questions in the affirmative, we will have the ability to save thousands of lives, reduce property loss by billions of dollars, and provide many billions of dollars in increased economic output.

We have chosen two illustrative cases to derive the characteristics of the systems that we must develop to enable these capabilities. The first is the *El Nino* Southern Oscillation (ENSO) and the second is a severe weather event such as a hurricane or thunderstorm

If one looks closely at the ENSO and the capabilities needed to make dramatically better seasonal to inter-annual predictions the following attributes for the end to end system are identified:

1) A large number ($\sim 10^5$) of *in-situ* sensors to provide closely spaced subsurface measurements of temperature and salinity,
2) Many parameters remotely sensed by satellite with fine spatial separation and high revisit rates,
3) Highly detailed and well coupled models of all portions of the land, ocean, and atmospheric systems,
4) Configurable sensors with embedded intelligence to rapidly adapt and optimize the observational systems to 'track' quickly changing macro-phenomena,
5) A flexible, adpatable end-to-end information system to ensure delivery of only the most useful and critical information (otherwise, items 1 and 2 could easily overwhelm any affordable data and communication system), and
6) A re-configurable, adaptable learning system with advanced human-machine integration because our scientific understanding and modeling/forecasting capabilities are evolving rapidly.

If one looks closely at severe weather events one identifies the following additional capabilities:

7) Sentinel systems to provide constant visibility, real-time response and autonomous tasking of other portions of the remote and *in-situ* sensing system,
8) Real-time, autonomous adaptive meshing in both the modeling/forecasting and sensing system,
9) Real-time data collection and fusion from many sources, and
10) Real-time warning and dissemination of localized and customized information products and forecasts.

The observational system will be described more in this paper while the remainder of the end to end information system and its operation are described further in a companion paper [Reference 1].

4 THE INTELLIGENT SENSORWEB

Achieving the attributes described in Section 3 in a cost-effective manner will require a very different architecture and system design than that used today. A wide variety of assets will be distributed in a wide range of vantage points from libration points, to GEO and LEO orbits, to *in-situ* sensors on probes, buoys, and un-piloted aircraft. The system will have a high degree of embedded intelligence and autonomy. Some platforms will function primarily as sentinels to recognize events and task other platforms to re-configure their sensors, positions, and formations to tailor their capabilities for observing new events. Virtual instruments and platforms can be formed at will, either autonomously or at the request. The overall system will be able to autonomously prioritize its activities by sensor, platform, geo-location, and time to ensure that the overall program-level goals are met while enabling agile and flexible responses. A robust calibration infrastructure will allow referencing of data from any source to well characterized standards and enable its use for long term climate change investigations as well as any other use requiring absolutely calibrated data. This will be achieved with a combination of calibration satellites, ground truth, high range and resolution sensors such as full hyperspectral spectrometers, as well as agile platforms to allow the viewing of natural calibration sources such as deep space or the Moon. Advances in miniaturization, low power techniques, and low cost production technologies will allow small satellites carrying the advanced sensors and information systems to be deployed in numbers that will ensure spatial coverage and temporal revisit rates sufficient for a wide variety of applications. Much like current day information networks, a plug and play architecture and standards will allow the seamless addition and deletion of components without affecting the operation of the other components. This strategy ensures that the system can rapidly evolve from precursor and subscale systems. It also ensures that new technology can be incorporated as quickly as it is available and needed since only very small portions of the overall capability will be placed at risk from any new technology insertion.

5 INTEROPERATION OF MODELING/FORECASTING SYSTEMS WITH THE OBSERVATIONAL SYSTEM

In order to ensure both effective and efficient operation, the Intelligent Sensorweb will be interoperable with the modeling and forecasting systems. In much the same way that some current modeling systems can auto-mesh to improve accuracy within limited computational capabilities, the sensing system will be directed and auto-meshed to tailor spatial, temporal, and spectral characteristics to the targets at hand. For example, the need to observe and predict the path and evolution of a severe storm might require that the sensing system re-configure to provide a much finer grid of observations, faster updates, as well as tailored spectral response in the region around the storm and along its projected path. Such behavior would exploit the available sensors and data bandwidth while providing higher quality reporting and predictions.

6 ACHIEVING THE VISION

Development of the complete flexible infrastructure described above is beyond the capability or responsibility of any one organization or country. In addition to the technological advances, the Earth science, applications, and user communities will have to reach agreement on the desirability of any and/or all of the attributes suggested. Agreements will have to be reached on the use and dissemination of data across military, government-sponsored science, government-sponsored operational, and commercial sectors. Agreements will have to be reached on a wide variety of standards and protocols. A partial list includes hardware signal and power interfaces, design and performance information standards, operational information and command (request) standards, priority and tasking protocols, observational information exchange and fusion standards.

It is not, nor should it be, NASA's role to impose a given set of attributes, architecture, or standards. However, NASA has a strong interest in a vibrant Earth science program which enables widespread and dramatically improved benefits to humankind. It is therefore our desire and intent to stimulate discussion of visions for the future of Earth science, applications, and the attendant technologies. By involving the global Earth science and applications community in defining the vision and setting the direction and strategies, we will have the opportunity to turn 'the dream of today' into 'the reality of tomorrow'.

1. Daniel S. DeVito, Janice K. Smith, Dennis J. Andrucyk, William J. Campbell, *Revolutionary Architectures for Future Earth Observations: Earth Science Information Web and Knowledge Creation*, 2nd IAA Symposium on Small Satellites for Earth Observation, (April 1999)